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ASSESSMENT OF CARBON LEAKAGE THROUGH THE INDUSTRY CHANNEL: THE EU PERSPECTIVE

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Abstract

Lack of consensus on an international agreement for reducing Greenhouse Gas Emissions (GHG) emissions eventually leads to asymmetric climate policies which not only increase the cost of reducing emissions but also decrease the effectiveness of the climate policy, through carbon leakage. We calculate the carbon leakage rate when EU undertakes a unilateral climate policy and we assess the importance of the competitiveness channel on carbon leakage. Our analysis is global and mirrors energy and climate policies and commitments that are currently announced at country level. The effectiveness of possible measures to mitigate carbon leakage is also evaluated and the results emphasize on the importance of the size of the group of countries participating in the GHG mitigation effort. The analysis is based on the results obtained using the GEM-E3 model, a global multi-sector and multi-country computable general equilibrium model. It is found that total carbon leakage is around 28%, over the 2015-2050 period, when the EU acts alone with moderate Armington trade substitution elasticity values; leakage rates are found to increase when assuming higher trade elasticities. The size and composition, in terms of GHG and energy intensities, of the group of regions undertaking emission reductions matter for carbon leakage. The paper finds that the leakage is significantly reduced when China joins the mitigation effort. If the USA joins the EU effort, the leakage rate drops only to 25% and if alternatively China joins the EU the leakage rate drops to 3% over the 2015-2050 period. This is attributed to both the market size of China and to

the energy intensity features of its production. Chemicals and metals are industries prone to higher leakage rates.

KEYWORDS

Carbon leakage, General Equilibrium, Climate Policy, GEM-E3, Industry relocation

JEL classifications: D58, Q54, Q43

1 INTRODUCTION

In the 15th UNFCCC[1] conference of parties held in 2009 in Copenhagen participating countries made different pledges to reduce their Greenhouse Gas (GHG) emissions by 2020. The emission reductions implied by these pledges are not enough to stabilize emission concentrations at safe[2] levels. Failure to reach a wide international agreement to reduce GHG emissions globally, eventually leads to asymmetric climate policies which not only increase the cost of reducing emissions but also decrease the effectiveness of the climate policy, because of carbon leakage [1].

Carbon leakage is defined as "*The part of emissions reductions in abating countries that may be offset by an increase of the emissions in the non-abating countries*" [2] and depends on: the magnitude of unilaterally performed GHG emission reductions, the exposure of the abating economies to foreign competition, the eventual measures[3] to counterbalance the adverse effects on industrial competitiveness, the technology spillovers and the size, both in terms of GHG emissions and GDP, of the countries involved in the abatement effort.

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[1] United Nations Framework Convention on Climate Change

[2] According to the Intergovernmental Panel on Climate Change (IPCC) (Fourth Assessment Report) global GHG emissions in 2050 should be reduced by at least 50% from 1990 levels

[3] Different measures have been proposed (but not always adopted) to protect the competitiveness of these industries including preferential allocation of grandfathered allowances to energy-intensive manufacturing, output based rebating (OBR) or border carbon adjustments (BCA).

Optimal (least cost) climate change mitigation at a global scale implies exploiting the cheapest emission reduction options across all regions and all sectors at the margin. As international climate negotiations made very slow progress in recent years, increasing skepticism prevails about the actual prospects of global concerted action against climate change. Consequently, the research has shifted towards regional climate action and the impacts of unilateral emission reduction policies. So carbon leakage can occur and effectively reduce emission reduction achieved in the carbon abating countries.

The channels through which carbon leakage occurs are: i) the energy channel (increase of energy consumption in non-abating countries induced by lower international fossil fuel prices due to emission reduction, hence lower fuel consumption, in the abating regions) and ii) the industry channel (due to different relative costs, energy intensive production partly shifts from countries applying emission reduction policies to countries that do not).

Carbon leakage raises concerns for climate policy especially in the EU which has decided to pursue ambitious targets for reducing GHG emissions [3] and [4]. The EU can be considered as a first mover in global GHG mitigation. The EU has established the worlds' largest emissions trading system (EU ETS), has already implemented a series of emission reduction, energy efficiency and RES deployment policies, and has confirmed a long-term objective to reduce GHG emissions in 2050 by at least 80% relative to 1990 levels.

The net macroeconomic impact on countries that pursue unilateral action in mitigating GHG emissions has been widely studied [5], [6], [7] and [8]. The net impact is uncertain as early movers incur costs but may also benefit from gaining a cost comparative advantage on producing low carbon technologies; the costs depend on the loss in competitiveness that leads to a decrease of their shares in global markets.

The purpose of this paper is to explore the effects of unilateral climate policy of the EU and quantify the carbon leakage within a dynamic and policy relevant framework by 2050. The paper also examines how the leakage rate changes if other regions join the ambitious emission reduction targets of the EU, such as China and the USA. The current paper is part of the AMPERE study on staged accession scenarios for climate policy (which is presented in detail in [38]). Apart a reference case projection, used as a benchmark for scenario comparison, the paper presents three alternative scenarios which vary regarding the extent of emission reduction coalition, namely the EU – only case, the China and the EU case and the USA and the EU case. As the leakage rate depends on the degree of competition in world trade[4] the (Armington [9]) substitution elasticity values are assumed to vary across sensitivity analysis scenarios. The sensitivity analysis assumes either uniform variation (i.e. doubling or halving elasticity values for all industries) or industry specific variation (different changes of elasticity values by sector).

The paper estimates carbon leakage rates from quantitative projections of the world economy, under different assumptions, using the GEM-E3 model, a computable general equilibrium model covering the whole world disaggregated into 37 countries/regions and 27 types of activity [10]. GEM-E3 is a recursive dynamic model with a bottom-up representation of the energy system and covers the period from 2010 to 2050 in 5-year steps. The model links all countries and sectors through endogenous bilateral trade flows.

The specification of the reference scenario takes into account the current fragmentation in global climate policies and includes a very detailed assessment of regional emission targets and thus it takes into account climate policies as currently announced by the various countries.

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[4] In the model domestically produced and imported commodities are considered as imperfect substitutes (Armington assumption).

The remainder of this paper is organized as follows. In Section 2 the paper provides a short review of the literature on carbon leakage. Section 3 summarizes the main channels and drivers of carbon leakage. Section 4 presents the model-based policy simulations. Section 5 discusses the results of the scenario projections and the sensitivity analysis. Section 6 draws concluding remarks.

2 LITERATURE REVIEW

A substantial empirical literature examining the issue of carbon leakage has already emerged. General equilibrium models have been used to quantify the carbon leakage rates for cases assuming that the EU or a larger coalition (i.e. Annex I countries of the Kyoto Protocol) unilaterally adopt GHG emission reduction policies. A leakage rate is defined as the ratio of emissions increased in the regions not pursuing climate mitigation actions over the emissions reduced in the regions applying emission reduction policies.

The Energy Modeling Forum EMF-29[5] carried out a model inter-comparison study with twelve static CGE models involved in the assessment of the role of Border Carbon Adjustment (BCA) in unilateral climate policies [1] and [11]. The EMF study shows that the sectors that present the higher carbon leakage rates are the energy intensive industries and generally the sectors with high exposure to foreign trade. The carbon leakage can be significantly reduced by the imposition of appropriate counter balance measures such as BCA, exemptions, output based allocations. However BCA and other measures such as exemptions and output based allocations are found to have distributional (among countries) and cost impacts.

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[5] "The Role of Border Carbon Adjustment in Unilateral Climate Policy"

The literature is not conclusive on whether the industry channel or the energy channel contributes more to carbon leakage. If the effects from the energy channel are canceled out (i.e. OPEC adjust its production so that international prices do not decrease) the leakage rate is reduced from 11.8 to 2.5 % [12]. But [13] suggests that when the adverse effect on the industry competitiveness is moderated, the leakage rate can be as low as 1% without accounting for leakage from the energy channel.

Leakage from the energy channel depends on the size of the economies that participate in the emission reduction effort and their energy intensity, as the impact on fossil fuel prices at global level depends on the volume of demand reduction. If emission reduction does not reduce demand for fossil fuels, as for example by employing carbon capture and storage, the effect on international fossil fuel prices can be modest.

Regarding unilateral climate action by the EU, it is obvious that the effects on world fossil fuel prices will be small given the relatively small importance of the region in global fuel demand. For a scenario where the EU reduces GHG emissions by 35% in 2030 relative to 2005 levels, and the rest of the world pursue modest climate policies, the models participating in the AMPERE project [14] have projected small decreases in world fossil fuel prices (0.7% for coal, 0.6% for oil prices and 0.2% for natural gas). A similar exercise[6] carried out using the Prometheus world energy model indicates a slightly more pronounced impact (world prices reduce by 1.3% for oil, 1.5% for gas and 2.3% for coal). If China joins the EU in the GHG abatement effort the models in the AMPERE project show fossil fuel price reductions of 7.7% for coal, 3.9% for oil and 1.6% for gas [14]. Similarly [15] and [16], have assumed virtually unchanged world fossil fuel prices for scenarios projecting unilateral climate mitigation action by the EU.

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[6] World energy scenarios quantified using Prometheus and POLES models for the preparation of [3] and [4]

In the EU the Emission Trading Scheme (ETS) legislation is implementing emission reduction policy. How industrial prices change as a result of EU ETS carbon prices is important for the leakage from the industry channel. Alexeeva-Talebi [17] using time-series analysis shows that additional costs induced by the EU ETS "*are likely to be absorbed through a reduction of profit margin, creating incentives to relocate business abroad*", mentioning that in the 1st EU ETS phase industry was able to pass through only 10-40% of the carbon price due to the little time that industry had in order to adjust its price. This contrasts findings by [18], [19] and [20] which assert that the opportunity costs passed through to consumers by the industry can be as high as 90%. This is because, even if granted for free under a grandfathering regime, permits have opportunity costs and so industrial prices are directly influenced by carbon prices, which further implies higher leakage rates.

The leakage rates estimated in the literature (Table 1) range from 2% to 130% and have a median value of about 20%.

Table 1: Literature review on carbon leakage rates and key determinants

Study	**Coalition**	**Emission target**	**Leakage rate**	**Model**	**Key points**
Böhringer et al [1]	Annex I with USA and without Russia	20% reduction from historical 2004 emission levels by 2020	3%-19% across the different models depending on model structure and the assumption about imposition of BCA.	Series of 12 static multi-sectoral, multi-regional CGE models	The imposition of BCA reduces carbon leakage (from 12% to 8% mean values by 2020) through the industry competitiveness channel.
Böhringer et al. [12]	EU	The EU reduces emissions by 20% until 2020 compared to BAU	9%-22%	Static CGE	Leakage rates vary with the assumptions about OPEC's behavior; If OPEC acts as a dominant produced leakage is reduced.
Matoo Aaditya et al. [13]	High Income countries of OECD (EU and USA)	17% emission reduction in the 2005-2020 period, carbon tax applied in the 2012-2020 period	Increase by 1% of the emissions in non-abating countries	Envisage (multi-regional dynamic recursive CGE)	When measures are taken to counterbalance the adverse effects on the energy intensive sectors the overall leakage rates range from 1 to 4%
Bauer et al. [14]	EU/ EU and China	EU follows the Roadmap targets/ EU and China follow the 450 ppm carbon price trajectory in the period 2010-2030	-11% to 63% depending on the size of the first mover coalition and specific model assumptions	12 global energy-economy Integrated Assessment Models	Leakage rates span a very broad range. Coal use is subject to smaller leakage effects compared to oil and gas.
Babiker [21]	Annex I	Kyoto targets imposed in the 1992-2010 period	25% to 130% depending on the market structure and substitution elasticity in trade*.	Static CGE	Market structure plays an important role in carbon leakage

Paltsev et al.[22]	Annex I	Regionally specified Kyoto targets (2008-2012 period) for EU, USA and Japan	10.5%	GTAP-EG (multi-regional dynamic recursive CGE)	The chemical sector is more vulnerable to leakage. China will be the main contributor to carbon leakage
Bollen et al. [26]	Annex I	Kyoto targets, period 2001-2020	20%	Worldscan (multi-regional dynamic recursive CGE)	Carbon leakage is affected more by the degree of substitution of energy in production
Gerlagh et al. [28]	Annex I +USA +Australia	Emissions 13-30% below baseline levels in the 2001-2010 period	14%-17%	CGE with endogenous energy saving and technology spillover	Carbon leakage in the presence of technology spillovers can be reduced or even be negative
Burniaux et al. [32]	Annex I	Kyoto targets for Annex I countries (1995-2010)	2.2% to 27.3% depending on coal supply elasticity and permit trade **	Green (CGE model identifying two world regions)	Supply elasticity of coal is an important factor affecting carbon leakage
Böhringer et al. [33]	Annex I	20% reduction from 2004 levels by 2020	2.5%	Static CGE	Carbon leakage is reduced from 11.8 to 2.5 if the energy channel is neutralized

* Low values occur under perfect competition and with low values of trade elasticity and high ones under oligopolistic competition and with perfectly homogeneous goods

** The low value refers to permit trade and coal supply elasticity equal to 2 and high value refers to no permit trade and .1 coal supply elasticity

The following summarize key findings in the literature regarding factors which determine carbon leakage rates:

<u>Market structure</u>: Babiker [21] finds that if oligopolistic competition prevails in the markets and if products are perfect substitutes (Heckscher – Ohlin assumption) the leakage rate can be as high as 130%. He further asserts that assuming perfect homogeneity of industrial products, carbon leakage is mainly driven by industry relocation.

<u>The allocation scheme and the market regime of carbon permits</u>: A common finding is that full trade of permits (within the carbon reducing coalition) reduces the leakage rate. Permit trading reduces the leakage rate by half [22]. The inclusion of a permit rebate mechanism decreases the leakage rate considerably [23],[1].

<u>The sectoral and regional aggregation</u>: Paltsev [22] points out that from a modeling perspective increasing regional detail lowers carbon leakage whereas increasing sectoral detail increases it. The EMF-29 multi model inter-comparison study states that the main qualitative conclusions about leakage do not change with the aggregation detail. Caron [24] uses a detailed industry dataset (51 industries instead of 16 of GTAP) to study the effects of sectoral aggregation on carbon leakage. He

claims that the model using less disaggregated sectoral detail does not lead to biased estimates of leakage.

Elasticity parameters: The elasticity values assumed by the models seem to largely influence the rates of carbon leakage. Alexeeva-Talebi [25] finds that the competitiveness effect for energy intensive industries is particularly sensitive (in magnitude and sign) to the choice of Armington elasticities. Bollen et al. [26] finds that carbon leakage is affected more by varying the degree of substitution of energy in production functions for energy consumers (energy efficiency) rather than the changes of carbon intensity in energy producing sectors (substitution of fossil fuels by low or zero carbon technologies). Balistreri and Rutherford [27] use an alternative trade theory based on Melitz [29] that includes heterogeneous firms operating within an oligopolistic competition market regime and they find that the trade effects on the energy intensive industries are more intense when endogenous productivity and entry dynamics are considered.

Adjustment in the energy supply side: Böhringer et al. [11] explore the importance of OPEC's behavior (the energy channel) for carbon leakage and finds that leakage rates vary from 4% to 22% depending on assumptions about OPEC's response to the EU's carbon pricing. Bauer et al. [14] perform a multi-model comparison of the impacts of fragmented climate policies on global fossil fuel markets and finds that carbon leakage through the energy channel is uncertain. The international re-allocation of fossil fuels use and the inter-fuel substitution effects lead to very different projections of leakage rates by the various models.

Technology spillovers: Gerlagh and Kuik [28] incorporate endogenous energy-saving technical change and international spillovers in a CGE model and find that the inclusion of spillovers decreases significantly carbon leakage. They also demonstrate that carbon leakage can become zero or even negative depending on technology improvement assumptions.

Transportation costs and trade patterns: Paltsev [22] finds that the features of bilateral trade greatly affect the magnitude of carbon leakage: high transportation costs prevent industry relocation and decrease carbon leakage.

Protection of energy intensive industries: Böhringer et al. [1] find that Border Carbon Adjustment (BCA) can effectively reduce emission leakage through the industry channel (mean model value of leakage rate falls from 12% to 8%) whilst improving global cost-effectiveness of unilateral climate action. However, Lanzi et al. [31] show that the imposition of BCA has adverse effects on the welfare of non-abating regions. They conclude that linking regional carbon markets is more effective compared to BCA as this mitigates global welfare losses arising from strong climate action. Mattoo Aaditya et al. [13] examine the impact of the BCA measure on regional welfare, energy intensive production and carbon leakage and finds that the leakage rate can be as low as 1 to 4% depending on the BCA implementation.

3 THE DETERMINANTS OF THE CARBON LEAKAGE CHANNELS

3.1 THE ENERGY CHANNEL:

The contribution of the energy channel to the carbon leakage depends on: i) the size of the economies that perform GHG mitigation action, ii) the carbon intensity of these economies, iii) the response of supply (i.e. fossil fuel producers) to demand reduction and iv) the type of fossil fuel which is substituted (for example trade of coal is limited as compared to gas and oil). World fossil fuel prices may decrease when demand reduces driven by emission reduction policies but market power of fossil fuel producers may well offset the impact of demand on prices. Small changes in global demand, as for example when the EU acts alone, may exert minimal effects on world fossil fuel prices.

In CGE models the demand for fossil fuels is derived from cost minimizing behavior of producers and utility maximization of consumers. Supply of fossil fuel is modelled using production functions which include fossil fuel resource as a primary production factor. As resources are limited, higher production implies higher prices of fossil fuels. Carbon leakage rates calculated from CGE models are found to be highly sensitive to the calibration of the fossil fuel supply elasticity. Boeters [34] showed that the standard CES formulation of supply leads to "*endogenously decreasing supply elasticities and sharply increasing marginal leakage rates for large coalitions that have ambitious emissions targets*". He proposes an alternative formulation to keep the fossil fuel supply elasticity constant.

Another important determinant of fossil supply in CGE models is whether resource extraction is calculated in a recursive dynamic process with myopic expectations or in inter-temporal optimization as the former tends to provide lower resource extraction rents. In the GEM-E3 model the supply of fossil fuels is price elastic, hence decreases in demand in abating countries lead to small decreases in fossil fuel prices. The resource extraction decision in GEM-E3 is endogenously determined in a recursive dynamic way. The dynamic evolution projected by the model is calibrated to projections by energy dedicated models, such as POLES or Prometheus.

3.2 THE INDUSTRY CHANNEL:

The European Commission decision (2010/2/EU) [35] lists the sectors and subsectors which, are deemed to be exposed to a significant risk of carbon leakage. These include the energy intensive industries producing chemical products, ferrous and non-ferrous metals, paper products, cement and other non-metallic minerals. The cost of energy in the total production costs of these industries is on average four times higher than in the other industrial sectors. The electricity and transport sectors mainly are oriented to the domestic markets and to intra-EU trade with limited exchanges with non EU regions. So electricity and transport are not considered to be subject to high leakage rates, unlike most of the energy intensive industries which are strongly exposed to foreign trade competition.

Energy intensive industries have a low share in GDP as they represent 7.6% of global value added in 2005 (Table 2) and employ 252 million persons (8.7% of global employment) but they have a much higher share in industrial energy consumption. At a world level the energy intensive industries account for nearly 60% of all energy used in the industrial sector: chemicals (29%), ferrous and non-ferrous metals (14.5%) and the nonmetallic minerals & pulp and paper (14.5%) (GTAP database [36]). At a regional level the most important producers of energy intensive products are the EU, the USA, Korea, Mexico, Taiwan, Indonesia, Russia, Japan and China (these regions jointly represent 89% of global value added) (Table 2).

Table 2: Importance of energy intensive industries in terms of value added

2005 (% shares in total value added)	EU27	China	USA	Japan	India	Russia	RoW(*)	WORLD
Metals	2.3	4.2	1.7	2.4	2.1	4.0	2.4	2.2
Chemicals	2.9	3.8	2.5	2.4	2.2	1.4	3.0	2.7
Other energy intensive	2.8	4.2	2.2	2.4	1.8	2.2	3.0	2.7
Total energy intensive	5.7	12.2	6.4	7.2	6.1	7.6	8.4	7.6
% Share of country in world total	32	7	25	11	1	1	14	

(*) for RoW mainly Korea, Mexico, Taiwan and Indonesia

In addition to the degree of exposure to foreign competition, carbon leakage rates also depend on certain industrial conditions, such as: i) the easiness of industrial relocation given that high transportation costs usually cluster the markets into certain geographical areas; ii) the degree of vertical integration and specialization in relation to other industrial and services activities which are not relocated; an example is the relations between metal industries and car manufacturing.

Openness to foreign competition can be measured both in domestic and international markets as the ratio of product output used for domestic purposes to its total supply and as the ratio of exports to total output. These measures are presented in Table 3 for the year 2005.

The data below suggest that the exposure of European industries to international trade is above world average. In particular, the chemicals industry is more exposed to foreign competition compared to other energy intensive industries, both in domestic and foreign markets. It should be noted however that a large share of exports of chemicals represent non energy intensive products such as pharmaceuticals.

Table 3: Trade openness of energy intensive industries

2005	**Metals**		**Chemicals**		**Other energy intensive**		**Total energy intensive**	
%	**D***	**I****	**D***	**I****	**D***	**I****	**D***	**I****
EU27	69	28	55	47	80	20	67	34
China	87	15	73	18	86	7	82	14
Japan	92	11	88	19	92	4	91	12
India	74	14	79	17	62	20	73	16
Canada	65	40	50	44	77	37	63	40
USA	83	7	79	18	90	6	83	11
Brazil	92	23	73	14	93	33	84	23
Oceania	84	31	64	14	90	17	80	21
Russia	83	52	58	50	77	21	74	45
ROW	72	26	69	23	82	17	73	22

* Trade openness in **D**omestic market (share of domestic production to total supply (domestic production + imports) - low values indicate high trade openness)

** Trade openness in **I**nternational market (share of domestic production directed to exports - high values indicate high trade openness)

4 THE MODEL

The GEM-E3 model as used in this study is calibrated on the GTAP v7.1 dataset and represents the economy split in 16 production activities (Table 4) three of which are energy intensive (chemicals, metals and other energy intensive). The model represents 37 regions covering the global economy. Each EU 27 member state is identified separately.

Table 4: Regional and sectoral detail of the GEM-E3 model.

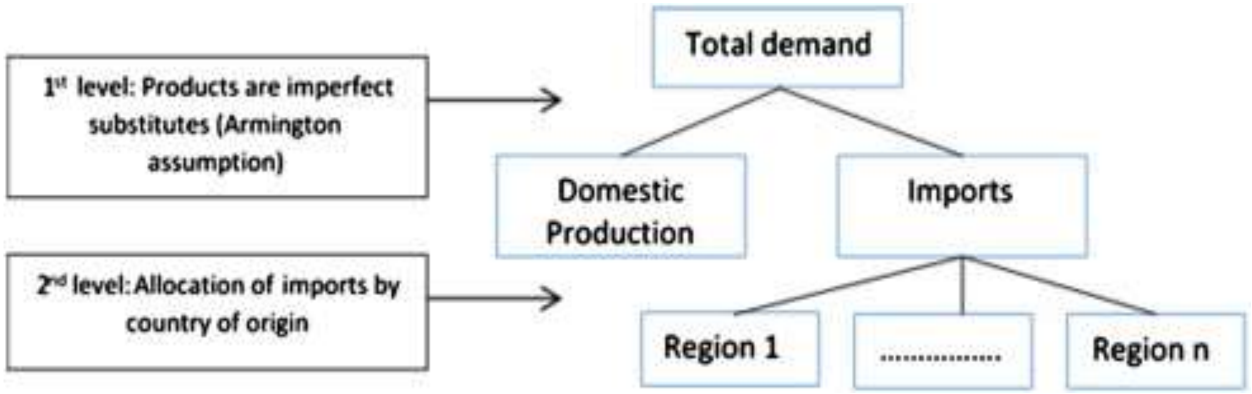
Countries-Regions		**Economic Sectors**	**Power Generation**
(USA)	The United States	Agriculture	Coal fired

(CAN)	Canada	Coal	Oil fired
(JPN)	Japan	Crude Oil and Oil refineries	Natural gas fired
(AUZ)	Australia & New Zealand	Natural gas	Nuclear
(FSU)	Russian Federation	Electricity Supply	Biomass
(CHN)	China	Ferrous & non-ferrous metals	Hydroelectric
(IND)	India	Chemical Products	Wind
(BRA)	Brazil	Other energy intensive	Solar
(ANI)	Rest of Annex 1	Electric Goods	Coal fired CCS
(ROW)	Rest of the World	Transport equipment	Gas fired CCS
(EU27)	MS are individually represented	Other Equipment Goods	
		Consumer Goods Industries	
		Construction	
		Transport	
		Market Services	
		Non Market Services	

Industries operate within a perfect competition market regime and maximize profits. Production functions consider possibility of substitution between capital, labor, energy and materials. The model identifies one representative firm for each economic sector. Household demand, savings and labor supply are derived from utility maximization using a linear expenditure system (LES) formulation, assuming exogenous population. Households receive income from labor supply and from holding shares in companies. Unemployment is endogenously projected following the efficiency wages approach [37]. Investment by sector is dynamic depending on adaptive anticipation of capital return and activity growth by sector. Capital markets clear at a global level assuming capital mobility between sectors and countries.

All regions and sectors are linked through endogenous trade flows. Total demand (final and intermediate) in each country is optimally allocated between domestic and imported goods, under the hypothesis that they are imperfect substitutes [9]. The supply mix is represented as a multi-level nested constant elasticity of substitution dual cost function: at the upper level firms decide on the optimal mix between domestically produced and imported goods; at the next level demand for imports is split by country of origin (see Figure 1).

Figure 1: Schematic representation of trade in GEM-E3



The cost minimization problem (for the upper level) of firm *s* in region *r* for time *t* is:

$$(1)\qquad \min C_{s,r,t} = PDP_{s,r,t} \cdot QDP_{s,r,t} + PIMP_{s,r,t} \cdot QIMP_{s,r,t}$$

Where $PDP_{s,r,t}$the price of domestically produced goods, $QDP_{s,r,t}$ represents production for domestic use, $PIMP_{s,r,t}$ is the import price and $QIMP_{s,r,t}$ is the quantity of imports. The demand for the composite good $Y_{\mathrm{s,r,t}}$ is specified as:

$$(2)\qquad Y_{\mathrm{s,r,t}} = AC_{\mathrm{s,r,t}} \cdot \left[\delta_{\mathrm{s,r,t}} \cdot QDP_{\mathrm{s,r,t}}^{\frac{\sigma_{\mathrm{s}}-1}{\sigma_{\mathrm{s}}}} + \left(1-\delta_{\mathrm{s,r,t}}\right) \cdot QIMP_{\mathrm{s,r,t}}^{\frac{\sigma_{\mathrm{s}}-1}{\sigma_{\mathrm{s}}}}\right]^{\frac{\sigma_{\mathrm{s}}}{\sigma_{\mathrm{s}}-1}}$$

Where $AC_{\mathrm{s,r,t}}$ is the scale parameter, $\delta_{\mathrm{s,r,t}}$ are the share parameters calibrated to base year data, and σ_{s} are the Armington elasticities of substitution between imported and domestically produced goods for each type of commodity. Optimal demand for domestic and imported goods is obtained by applying Shephard's lemma.

$$(3)\qquad QDP_{s,r,t} = \begin{cases} \mathrm{Y_{s,r,t}} \cdot \mathrm{AC}_{\mathrm{s,r,t}}^{\sigma_{\mathrm{s}}-1} \cdot \left(1-\delta_{\mathrm{s,r,t}}\right)^{\sigma_{\mathrm{s}}} \cdot \left(\frac{PY_{s,r,t}}{PDP_{s,r,t}}\right)^{\sigma_{\mathrm{s}}} & \text{if } \mathrm{AC}_{s,r,t} \neq 0 \\ \mathrm{Y_{s,r,t}} & \text{if } \mathrm{AC}_{s,r,t} = 0 \end{cases}$$

$$(4)\qquad QIMP_{s,r,t} = \mathrm{Y_{s,r,t}} \cdot \mathrm{AC}_{\mathrm{s,r,t}}^{\sigma_{\mathrm{s}}-1} \cdot \delta_{s,r,t}^{\sigma_{\mathrm{s}}} \cdot \left(\frac{PY_{s,r,t}}{PIMP_{,s,r,t}}\right)^{\sigma_{\mathrm{s}}}$$

Table 5 contains the upper-level Armington elasticity values used in the GEM-E3 model. The Armington elasticities differ among sectors, but are identical for all countries/regions. Homogeneous products, like the energy products, are assumed to have high elasticity values.

Table 5: Substitution elasticities between domestically produced and imported goods

Agriculture	2.91	Electric Goods	4.40
Coal	6.10	Transport equipment	3.55
Oil	7.30	Other Equipment Goods	3.90
Natural gas	10.0	Consumer Goods Industries	3.21
Ferrous & non-ferrous metals	3.63	Construction	1.90
Chemical Products	3.30	Transport	1.90
Other energy intensive	2.25	Market Services	2.03

5 POLICY SCENARIOS

5.1 SCENARIO DEFINITIONS

The scenario design is based on the AMPERE[7] project specifications, regarding GDP, population and climate policies assumed for the reference scenario (the AMPERE scenarios are described in detail in [38]). All scenarios including those for sensitivity analysis purposes were quantified using the GEM-E3 model. On the basis of scenario projections we calculate the carbon leakage rates. The main scenarios used in this paper are as follows:

Reference (RefPol[8]): A moderate climate policy scenario assuming fragmented and non-harmonized climate policies by country. The scenario assumes that the countries will implement

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[7] See http://ampere-project.eu/web/

[8] The abbreviations of the scenario follow AMPERE project definitions

the low end of their Copenhagen-Cancun pledges (Table 6) until 2020. After 2020, it is assumed that the countries continue climate policies in order to achieve emissions intensity improvements comparable to the period before 2020. Achievement of emission reduction targets are simulated by determining the appropriate level by country (or region as for example in the EU) of payment for carbon emissions. The carbon prices apply uniformly on all sectors belonging to the EU-ETS. Specifically for the EU the scenario includes all bottom-up policies that are already adopted towards the implementation of the 2020 energy and climate policy package. Regarding EU ETS allowances, a linear annual reduction of the ETS cap is considered and free granting of allowances is gradually abolished until 2020, according to the provisions of the ETS Directive. It is obvious in Table 6 that the pledges correspond to different abatement efforts by country and thus the reference scenario includes asymmetric climate actions which may lead to carbon leakages.

Table 6: Regional climate targets in GEM-E3 model in the moderate climate policy reference scenario

Region	GHG emissions reduction in 2020 from 2005	GHG intensity reduction in 2020 (from 2005)	RES share in electricity in 2020	Installed RES capacity targets in 2020	Installed nuclear capacity in 2020	GHG intensity improvement after 2020 (in % p.a.)
EU-27	-15.0%		20.0%[9]			3.0%
China	N/A	-40%	25.0%	Wind: 200 GW, Solar PV: 50 GW	41 GW	3.3%
India	N/A	-20%		Wind: 20 GW, Solar PV: 10 GW	20 GW	3.3%
Japan	-1.0%			Wind: 5 GW, Solar PV: 28 GW		2.2%
USA	-5.0%		13.0%			2.5%
Russian Federation	27.0%		4.5%		34 GW (2030)	2.6%

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[9] In gross final energy demand

AUZ	-13.0%		10.0%			3.0%
Brazil	-18% (from BAU)					2.7%
Rest of the World	-6.2% (from BAU)			Wind: 8 GW		2.0%
Canada	-5.0%		13.0%			2.4%

The reference scenario projects energy intensive industrial production gradually shifting from the OECD countries to China, India and to other world regions. The share of the OECD countries in world production drops from 67% in 2005 to 43% in 2030. The EU share is projected to fall by 10 percentage points (from 34% to 24%). Domestic production of chemicals is projected to decrease in absolute terms in Canada, the Russian Federation and Japan. On the other hand, production in China and India is projected to more than quadruple in the period 2005-2030, driven by low production costs, rising domestic demand and a big expansion of Chinese exports inducing further industrial integration. The share of China and India in world production of energy intensive products rises from 12% in 2005 to 31% by 2030.

These trends are in line with EIA [39] and World Bank [40] studies which project industrial energy consumption of China and India (60% of which correspond to chemicals, metals and non-metallic minerals industries) to double in 2030 from 2008 levels, whilst OECD countries continue past trends shifting GDP structure from manufacturing to services.

Fossil fuel prices in the reference scenario are projected to increase: more in the short/medium term but more slowly in the long term (Table 7).

Table 7: World fossil fuel prices in international trade projected for the GEM-E3 reference scenario

Annual rates of change of prices in constant dollars per unit of energy	1990-2000	2000-2010	2010-2020	2020-2030	2030-2040	2040-2050
Oil	-0.93	9.07	0.44	1.82	0.93	0.88
Gas	-1.32	7.99	1.51	2.12	1.26	1.26
Coal	-7.77	8.72	2.40	1.29	0.00	0.28

Source: GEM-E3

EU-Only (RefP-EUback): In this scenario it is assumed that from 2015 to 2030 the EU implements the Low-Carbon Economy Roadmap [3] and [4] and the non EU countries continue with the Cancun pledges as in the reference case. After 2030, the EU gradually moderates the ambition of the emission reduction effort because of lack of comparable emission reduction effort in the rest of the world and reverts back to the reference scenario carbon price by 2050.

EU-CHN: The EU and China join efforts and pursue in common an ambitious emission reduction effort until 2030. The other regions follow the policies assumed in the reference scenario. After 2030, both the EU and China decelerate climate effort and by 2050 apply their respective reference scenario carbon prices.

EU-USA: The EU and the USA join efforts and pursue in common an ambitious emission reduction effort until 2030. The other regions follow the policies assumed in the reference scenario. After 2030, both the EU and the USA decelerate climate effort and by 2050 apply their respective reference scenario carbon prices.

The AMPERE study [38] also considers two staged accession scenarios in which the EU (or the EU and China) act as first movers in climate policies and successfully motivate other regions to join an ambitious climate policy regime in 2030. The success scenarios were not examined in this paper as the potential for carbon leakage is significantly reduced after 2030 since all countries participate in the 450 ppm global mitigation effort. On the contrary, carbon leakage can be better evaluated in the EU-Only and EU-CHN scenarios, which include asymmetric climate policies in world regions even after 2030.

Table 8: Carbon prices in the various scenarios

$ 05' per tCO2		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Reference	EU	14	24	25	43	78	116	148
	China	0	0	0	0	1	8	15

	USA	0	14	21	35	56	70	78
EU – Only	EU	37	63	83	99	116	132	148
	China	0	0	0	0	1	8	15
	USA	0	14	21	35	56	70	78
EU - CHN	EU	37	63	83	99	116	132	148
	China	37	63	83	66	49	32	15
	USA	0	14	21	35	56	70	78
EU - USA	EU	37	63	83	99	116	132	148
	China	0	0	0	0	1	8	15
	USA	37	63	83	82	80	79	78

Source: GEM-E3

The carbon prices assumed by scenario are shown in Table 8. As the purpose of the scenarios is to explore the range of values of carbon leakage, we apply the same carbon prices by scenario so as to ensure comparability. The carbon prices are endogenously calculated only in the reference scenario in order to simulate that the countries achieve their emission pledges. In addition to the carbon prices, the scenarios with stronger climate policies than in reference assume accelerated learning leading to reduction in capital costs for low and zero carbon technologies, mainly in power generation. In this study, technology costs do not differ by region and do not depend on whether or not a country is a first-mover in climate policy[10]. In the decarbonisation scenarios, bottom-up measures facilitating energy savings in buildings and transport electrification are also introduced. The bottom up measures aim at removing non market barriers in these sectors and thus at enabling higher effectiveness of carbon prices.

The payments by carbon emitters are assumed to go to the state and return back to emitters through a revenue recycling scheme. As we found that model results are sensitive on the choice of the revenue recycling scheme, we carried out simulations for a range of different schemes,

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[10] Capros et al [5] analyzed the macroeconomic costs and benefits for the EU as a first mover in climate change mitigation and found that induced technological change has a critical role in reducing decarbonisation costs in all regions and hence in reducing carbon leakage.

including: i) reduction of labor costs (via reductions of employers' social security contributions), ii) financing of R&D in low carbon power generation technologies, iii) subsidization of power generation from renewable energy sources, iv) lump-sum transfer to households and v) reduction of indirect taxes imposed on production. We ranked the recycling options in terms of their implications[11] on GDP, welfare and employment and for this study we have used only a scheme where carbon revenues are given to households as lump-sum transfers because this scheme minimizes impacts on welfare.

5.2 RESULTS

5.2.1 MACROECONOMIC EFFECTS

Carbon pricing induces changes in the economy driven by substitution away from fossil fuels and lower energy consumption per unit of activity or income. To enable these changes higher capital investment is required as both low emitting technologies and energy savings are capital intensive. The changes away from fossil fuels are costly and energy services[12] become more expensive in all sectors compared to situation without carbon pricing. The increased costs of energy services imply lower purchasing power of private income and thus lower demand and higher prices in the supply of goods and services due to higher costs further implying decrease of demand. The additional investment in clean technologies and in energy savings which are required to decrease fossil fuel consumption has opposite effects on demand which increases for those goods and services that are needed to build the new efficient equipment, the clean power plants and for insulating buildings.

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[11] A detailed analysis on the impact on alternative recycling options has been performed within the MODELS EC funded project, http://www.ecmodels.eu/index_files/Page660.htm.

[12] Useful energy services delivered by using purchased energy commodities and equipment as well as energy saving capital at the user's premises, factory or vehicle.

The numerical simulations in this paper, in agreement with the literature, find that the net effect on activity is negative, compared to a situation without carbon pricing, because of higher costs which depress demand, as in the absence of induced productivity effects income generated by primary production factors (capital and labor) does not have potential to increase. If carbon pricing applies unilaterally in an open economy competitiveness in foreign markets weakens implying further reduction of domestic activity. Part of the potentially cleaner domestic activity is thus substituted by foreign activity which eventually emits more carbon dioxide, as the latter is not subject to carbon pricing. Therefore carbon prices are less effective than initially expected and carbon leakage occurs.

The projections using the computable general equilibrium model GEM-E3 confirm that the countries applying carbon pricing unilaterally see diminishing activity and GDP compared to a reference scenario which does not involve such carbon pricing. Even if these countries have strong industrial know how so as to build domestically the clean and energy efficiency investments, the corresponding activity is not found sufficiently high to offset the activity depressing effects stemming from higher costs and prices.

The burden of carbon pricing in the economy depends on the degree of carbon intensity and on the marginal costs of emission reduction. The EU has the lowest carbon intensity (greenhouse gas emissions per unit of GDP) among the regions included in the model and this mainly explains why the net costs calculated as GDP percentage loss are lower than in other regions when applying equal carbon prices.

The model results indicate that EU's GDP decreases in all cases examined compared to the reference case (Table 9). Competitiveness losses are obviously higher in the EU-only scenario, compared to the cases where equal carbon prices apply also in other regions. So EU's GDP loss is higher in the EU-only scenario compared to the EU-China and the EU-USA cases. The Chinese economy is highly carbon intensive and applying carbon prices at equal level as on the EU implies higher carbon costs amount as percentage of GDP in China. The Chinese economy is also highly energy intensive (relative to GDP) because of low energy prices also due to low energy taxation. Therefore pricing carbon equally as in the EU implies higher rate of change of energy prices in China than in the EU. These differences imply higher GDP losses in China than in the EU when applying equal carbon prices, despite China having larger and cheaper emission reduction potential than the EU. Similar arguments explain why GDP losses are higher for the USA than for the EU when applying equal carbon prices: the USA economy is more carbon and energy intensive and has lower energy prices and taxation than the EU. The impacts on the USA are however smaller than on China.

According to the model results the cumulative GDP losses over the period 2016-2050 are 0.20% below reference scenario GDP in the EU-only scenario. In the EU-China scenario the cumulative GDP losses of the Chinese economy are close to 2% below reference, and the USA GDP losses in the EU-USA scenario are 0.31% below reference.

The countries which do not apply additional carbon pricing relative to the reference get activity benefits owing to higher competitiveness but also get activity losses because demand for their products reduces as other countries apply additional carbon pricing and experience depressive effects on domestic demand. The net effect on GDP of countries not participating to climate policy is small, either slightly positive or slightly negative. The net effect on global GDP is slightly negative in all climate action scenarios as compared to the reference scenario.

The negative impact on GDP of countries pursuing unilateral carbon pricing is lower in the period after 2030, than before 2030. This is due to the assumption that after 2030 the carbon prices tend to converge to reference carbon prices in 2050 but they remain above reference price levels in the period 2030 to 2050.

Table 9: GDP impact of different scenarios

% change of GDP from reference scenario		**2020**	**2030**	**2050**	**cumulatively over 2016 - 2030**	**cumulatively over 2031 - 2050**
EU – Only	**EU**	**-0.20**	**-0.36**	**-0.02**	**-0.24**	**-0.18**
	USA	-0.01	-0.01	0.02	-0.01	0.01
	China	0.01	0.02	-0.02	0.02	0.00
	Rest of World	-0.01	-0.01	0.08	-0.01	0.05
EU - CHN	**EU**	**-0.18**	**-0.34**	**-0.02**	**-0.22**	**-0.16**
	USA	0.03	0.01	0.04	0.03	0.02
	China	**-1.34**	**-2.34**	**-2.04**	**-1.70**	**-2.05**
	Rest of World	-0.13	-0.18	0.14	-0.16	0.04
EU - USA	**EU**	**-0.19**	**-0.35**	**-0.02**	**-0.24**	**-0.18**
	USA	**-0.37**	**-0.53**	**-0.09**	**-0.40**	**-0.27**
	China	0.05	0.11	-0.02	0.07	0.03
	Rest of World	-0.04	-0.04	0.14	-0.04	0.09

Source: GEM-E3

Demand for energy intensive commodities tends to decrease in countries applying carbon pricing because of demand reduction in the entire economy although the energy-intensive commodities participate more than other commodities in the building of clean energy related investment. Activity reduction of energy intensive industries is also driven by loss of competitiveness in case carbon pricing is unilaterally applied, and this effect is higher than for other industrial sectors depending on carbon intensiveness. The decrease in activity in countries applying unilateral carbon pricing also depends on the degree of exposure to foreign trade.

Table 10 shows activity losses in energy intensive industries in the scenarios that assume asymmetric climate policies, relative to the reference scenario projection. The losses in "other energy intensive" sectors are lower than in metals or chemicals, because cement, building materials and paper are less traded. The decrease in energy intensive industrial production takes place in the entire group of countries which unilaterally apply carbon pricing and part of the decreased activity is relocated in countries not applying the carbon pricing policy. Within the group of countries applying the unilateral policy, the relative shares of the countries in energy intensive industrial production change depending on their relative competitiveness. For example, because in the EU-

China scenario the Chinese economy encounters higher cost impacts than the EU, energy intensive industrial production is found to increase in the EU and strongly decrease in China, while the activity reduces for the sum of energy-intensive industrial production by the EU-China group. A different result is found for the EU-USA scenario, where energy intensive industrial production decreases in both the EU and the USA.

Table 10: Impacts on energy intensive industrial production in the EU

Change of cumulative production from reference	EU - Only			EU - CHN			EU - USA		
	in %	in %	in b$'2004	in %	in %	in b$'2004	in %	in %	in b$'2004
	2016-2030	2031-2050	2016-2050	2016-2030	2031-2050	2016-2050	2016-2030	2031-2050	2016-2050
EU production									
Ferrous and nonferrous metals	-1.47	-1.39	-587	0.84	0.64	296	-1.45	-1.34	-570
Chemical Products	-1.43	-0.86	-720	0.48	0.25	226	-1.05	-0.66	-542
Other energy intensive	-0.91	-0.67	-400	-0.50	-0.39	-226	-0.79	-0.61	-356
China production									
Ferrous and nonferrous metals	0.24	0.24	118	-13.48	-11.86	-6061	0.14	0.20	85
Chemical Products	0.42	0.14	171	-9.31	-5.70	-5202	0.67	0.22	275
Other energy intensive	0.08	0.05	18	-7.02	-4.85	-1634	0.12	0.07	25
USA production									
Ferrous and nonferrous metals	0.04	0.09	15	2.47	2.20	477	-0.61	-0.08	-60
Chemical Products	0.31	0.15	59	2.79	1.53	569	-2.52	-1.32	-504
Other energy intensive	0.11	0.06	19	0.82	0.46	148	-1.39	-0.64	-229
Rest of World production									
Ferrous and nonferrous metals	0.17	0.09	123	2.88	2.43	2656	-0.10	-0.01	-43
Chemical Products	0.30	0.12	192	1.60	0.75	1109	0.40	0.21	293
Other energy intensive	0.13	0.09	74	0.50	0.40	308	0.12	0.11	82

Source: GEM-E3

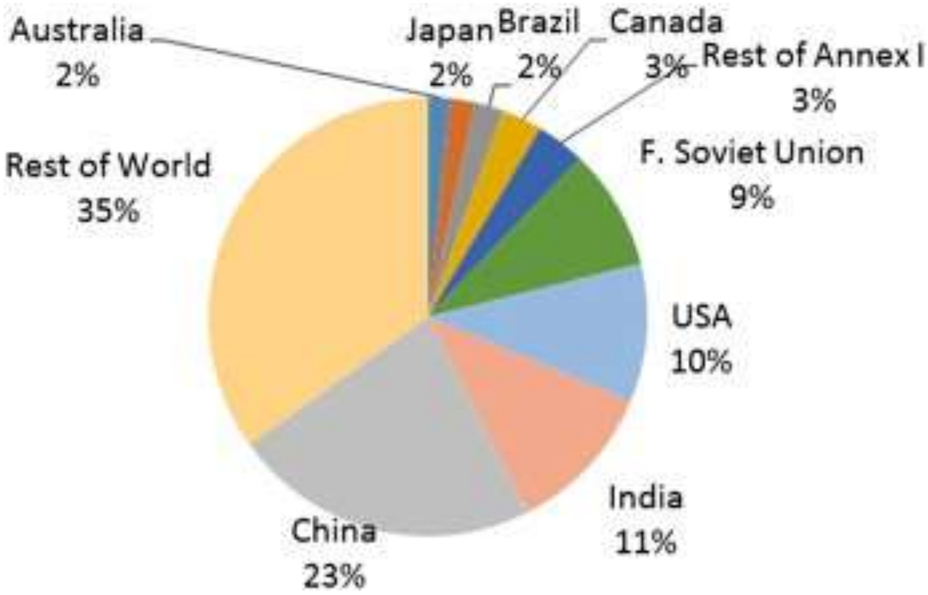
The effects beyond 2030 are lower than before 2030 because of the carbon price trajectories relative to the reference scenario, however the impacts until 2030 are roughly maintained in the time period after 2030. This is also due to dynamic mechanisms showing investment by sector to slow down until 2030 in countries applying unilateral carbon prices, being influenced by low rate of return prospects. The decreased return before 2030 continues to negatively influence investment also after 2030.

5.2.2 REGIONAL CARBON LEAKAGE

We calculate regional carbon leakage as the increase of emissions, relative to reference projection, in countries which do not apply to carbon pricing. The ratio of leakage is expressed as a percentage of regional carbon leakage over the amount of emission reduction in countries which apply carbon pricing. We also calculate leakage amounts and rates in cumulative terms over a time period.

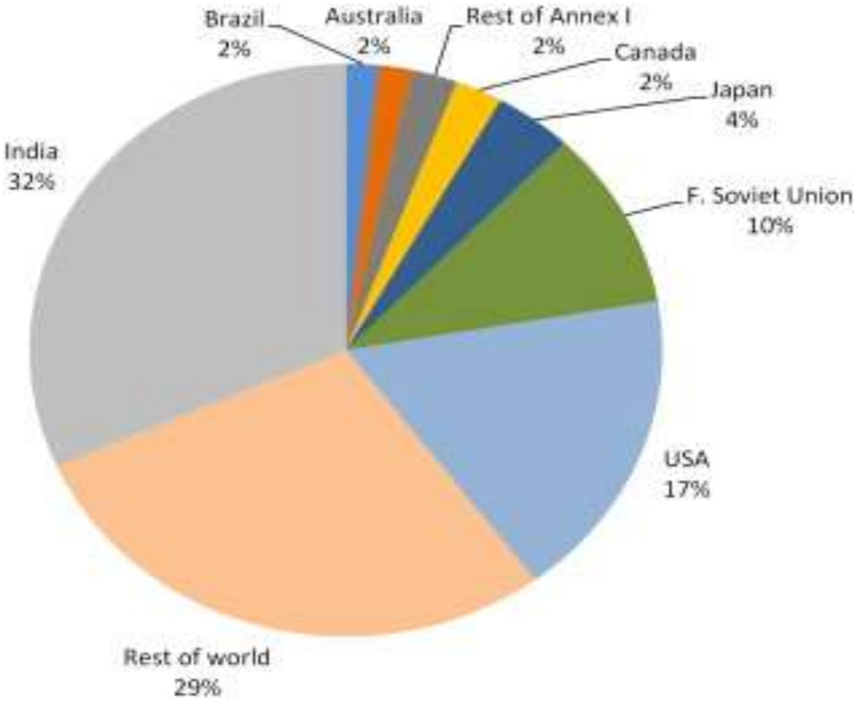
Based on the projections in the EU-Only scenario, the EU carbon leakage rate is 21.6% cumulatively over the period 2015-2030 and 27.7% over the 2015-2050. The EU reduces CO_2 emissions by 6.64 Gtn of CO_2 cumulatively over 2015-2050, while in other regions emissions increase by 1.84 Gtn. The regions/countries where carbon leakage occurs are Rest of World, China, India, the United States and Russia which mainly increase emissions in the EU-only scenario relative to the Reference. Figure 2 shows the carbon leakage amounts as regional shares, calculated in cumulative terms until 2050. The increase of emissions in the non-EU countries, due to leakage, represents only 0.1% of reference scenario cumulative emissions in these countries.

Figure 2: Regional decomposition of carbon leakage (shares in %), EU-only scenario, cumulative emissions 2011-2050.



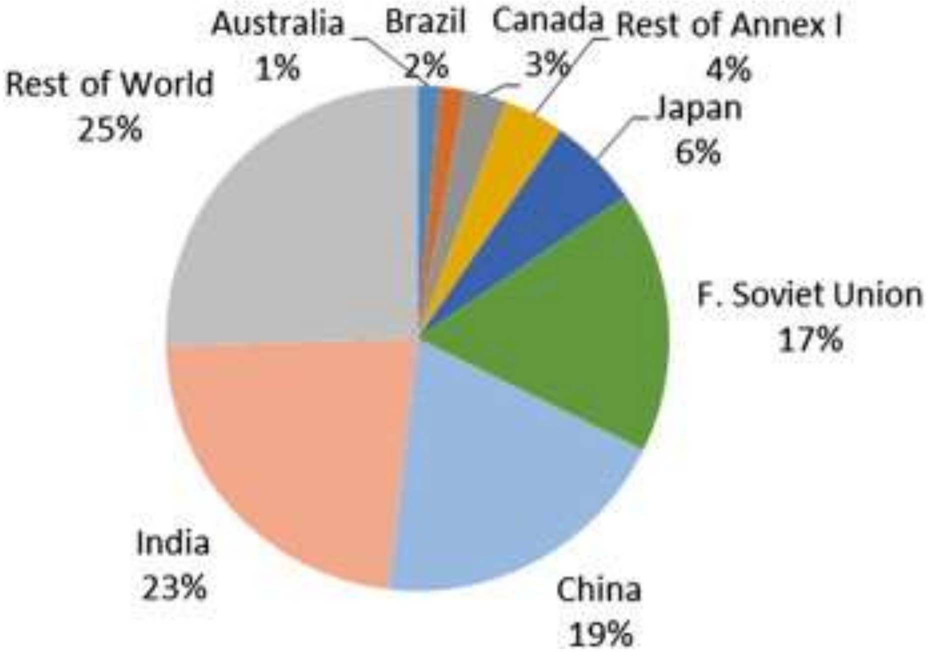
When China and the EU jointly apply carbon pricing as in the EU-China scenario, the rate of carbon leakage is significantly reduced. Cumulatively in the period from 2015 to 2050, EU and China CO_2 emissions are reduced by 217.2 Gtn relative to reference scenario levels, whereas the emissions of other countries increase by 6.4 Gtn. This implies a leakage rate of 2.9% which is 2% for cumulative emissions during 2015-2030. In the EU-China scenario emissions mainly increase in Rest of World and in India which jointly account for 1.8 percentage points of the overall 2.9% leakage rate (Figure 3). The amount of emissions increased in countries not applying carbon pricing is larger in the EU-China scenario compared to the EU-Only scenario, but the amount of emission reduced jointly by the EU and China in the former scenario are much larger than in the latter scenario. This implies a decrease of the leakage rate which becomes very small in the EU-China scenario mainly because the Chinese emissions are large and reduce very significantly in the EU-China scenario. Therefore the size of the countries which participate in joint emission reduction effort matters for the leakage rate: larger country size implies lower leakage rate. It can be also seen in the model results that the carbon price is more effective in reducing emissions in countries which are inefficient in terms of energy and carbon intensity, such as China. The same level of carbon price implies much higher rates of decrease in emissions in China than in the EU. Therefore the inclusion of inefficient economies, in terms of energy and carbon, in the group of countries applying carbon pricing also matters for the carbon leakage, implying lower rates of leakage. The energy prices substantially increase in China in the context of the EU-China scenario but because Chinese industrial costs are lower than in competing countries, the increased energy costs have smaller effects on relative competitiveness than a case where similar energy price increases take place in a country with higher industrial costs. Therefore, including low industrial cost countries in the group applying emission reduction also implies lower leakage rates.

Figure 3: Regional decomposition of carbon leakage (shares in %), EU-China scenario, cumulative emissions 2011-2050.



In the scenario where the USA and the EU jointly apply carbon pricing, the rate of carbon leakage is reduced compared to the EU-Only scenario but by significantly less than in the EU-China scenario. The reasons are twofold: the USA economy has more limited emission reduction potential compared to China for the same level of carbon prices and the effects of carbon prices on competitiveness of the USA are higher than for China. Nevertheless, the carbon leakage rate over the period 2015-2030 is 11.5% that is well below the rate in EU-only scenario. The leakage rate is shown to increase in the time period after 2030 and become 25.2% in cumulative terms over 2015 - 2050, which is slightly below the rate in the EU-only scenario. The rise of carbon prices in the USA implies tapping on low cost opportunities for emission reduction, which exist in the USA because of low energy taxation (contrasting the EU) but which are exhausted in the short/medium term making further emission reduction more costly in the longer term. The EU-USA coalition for emission reduction does not imply large gains in terms of leakage, contrasting the EU-China coalition.

Figure 4: Regional decomposition of carbon leakage (shares in %), EU-USA scenario.



In all scenarios examined the highest leakage is registered in regions characterized by low production costs (mainly low wages) such as rest-of-the-world, former Soviet Union and India. The leakage rates are presented in Table 11. The projected leakage rates for the EU-only and the EU-USA cases stand close to highest end of the range reported in the literature. By contrast, the rate for the EU-China case is among the lowest reported in the literature.

This illustrates that the composition of the countries coalition for climate mitigation is of high importance for estimating the carbon leakage rate. The reasons mentioned above refer to size of the coalition, the effectiveness of carbon pricing for emission abatement and the inclusion of low cost, hence competitive, economies in the coalition.

Table 11: Leakage rates in the different scenarios

	2015 - 2030	2015 - 2050
EU - Only	21.6%	27.7%
EU - CHN	1.8%	2.9%
EU - USA	11.5%	25.2%

5.2.3 LEAKAGE THROUGH THE ENERGY CHANNEL

Carbon leakage through the energy channel (also termed fossil fuel price channel) is meant as the increased emissions in countries not applying climate mitigation policies as a result of higher consumption of fossil fuels induced by lower international fossil fuel prices due to global demand reduction in countries which apply climate mitigation policies. This definition clearly points to fossil fuel prices as the cause of emission increase. The carbon leakage through the industrial channel implies that energy consumption, including fossil fuels, increases in countries not applying climate mitigation. To avoid double counting the carbon leakage through the energy channel must be measured only as a consequence of varying fossil fuel prices due to lower global demand for such fuels.

The size of carbon leakage through the energy channel primarily depends on the supply response of fossil-fuel producers, so that if fossil fuel supply is inelastic then carbon leakage risks to be large. In particular, coal supply responsiveness is important for the size of carbon leakages. Regarding coal, the degree of global market integration matters for estimating coal supply elasticity. At present a small fraction of coal production is traded (roughly 15% worldwide) which implies that trade exposure of coal is rather small. This further implies that coal related leakage is small, since decreasing coal demand would well imply lower production rather than cheaper exports.

The gas and oil global markets are characterized by high rents much above production costs, due to oligopolistic supply. In addition, future supply depends on exploiting non-conventional and yet to find resources, which are characterized by high production costs. Assuming reduced demand for these hydrocarbons in the future would cancel development (at least partly) of new potential resources which would imply continuation of currently high concentration of supply, and thus continuation of high oligopolistic rents. High supply elasticity should then be expected for gas and oil supply.

In GEM-E3 the supply of fossil fuel production is assumed to be quite elastic for the reasons summarized above. Thus the leakage through the energy channel is small as the decreased demand for fossil fuels in abating countries produces small reductions in fossil fuel prices (Table 12). The small variation of fossil fuel prices in the GEM-E3 model is also attributed to the penetration of carbon capture and storage (CCS) in the long term which implies that demand for coal and gas is not as significantly reduced as it would be expected in the absence of the CCS option.

Table 12: Impacts on fossil fuel prices (world average)

% change from reference		**2020**	**2030**	**2040**	**2050**
EU - Only	Coal	-0.24	-0.92	-1.22	-0.90
	Oil	-0.59	-1.81	-1.51	-0.11
	Gas	-2.27	-5.79	-4.06	-0.07
EU - China	Coal	-5.30	-11.58	-6.86	-0.53
	Oil	-0.45	-3.16	-2.48	-0.09
	Gas	0.18	-3.28	-2.90	-0.07
EU - USA	Coal	-0.29	-1.36	-1.43	-0.87
	Oil	-2.47	-5.40	-3.13	-0.12
	Gas	-6.09	-12.39	-6.79	-0.04

Different estimations of leakage from energy channel have been published. For example [41] postulates that the coal market is globally integrated and competition is close to be perfect implying that coal prices decrease as a result of lower consumption in Kyoto protocol's Annex I countries and coal demand considerably increases in non-Annex I countries.

5.2.4 CARBON LEAKAGE BY SECTOR

Industry relocation in the model is implicit and is depicted as change of regional shares in total production. When carbon prices apply asymmetrically on a region (or on a group of regions), the resulting changes in regional production costs drive changes in regional shares and thus production increases in countries that do not participate in the GHG mitigation action.

Table 10 shows the impacts on production of energy intensive industries in the context of the three scenarios which involve asymmetric carbon pricing. An important observation is that the amount of production decreased in the group of countries applying carbon pricing is higher than the amount of production increased in countries not applying carbon pricing. This is because global demand for the energy intensive products overall decrease in scenarios with carbon prices compared to the Reference, as restructuring towards less energy intensive products take place as a result of carbon prices. This restructuring obviously reduces the carbon leakage rate. Due to size effects, the amounts of production relocated are highest in the EU-China case and lowest in the EU-Only case. The sectors of chemicals and metals, as being more exposed to foreign competition, bear higher relocation impacts than the sector of other energy intensive products (among which cement and other building materials) which due to high transportation costs need to be located close to consumption.

When China and EU jointly reduce their GHG emissions, the Chinese energy intensive industrial production falls by 8.3% on average cumulatively over 2015-2050 period as the impact of carbon pricing is higher on low cost producers such as China, whereas the impacts on the EU's industrial production are lower than in the EU-Only scenario as the competitiveness of European exports compared to Chinese is improved compared to the EU-Only scenario.

Table 13: Industrial leakage by sector (EU- only)

	Carbon leakage rates by sector (%)			Difference of cumulative emissions from Reference (2016 - 2050) Mt CO2	
EU-Only Scenario	2020	2030	2016-2050	Non abating countries	Abating countries
Industry	12.2	14.5	19.8	575	-2908
Energy Intensive	16.7	19.2	20.2	314	-1556
Metals	12.0	28.4	29.2	115	-393
Chemicals	43.5	31.3	35.0	95	-272
Other energy intensive	9.0	11.2	11.7	104	-891
Rest of Industries	8.0	9.0	19.3	261	-1352
Energy (incl. Power Generation)	40.1	30.6	37.5	1253	-3345
Services	-18.0	-16.8	-6.9	-15	-224
Households	-0.5	-4.3	18.3	30	-165
Total	**22.8**	**21.8**	**27.7**	**1843**	**-6643**
EU-China Scenario	2020	2030	2015-2050	Non abating countries	Abating countries
Industry	0.2	0.3	0.9	528	-59010
Energy Intensive	3.4	4.4	4.5	1095	-24320
Metals	2.9	4.6	4.1	531	-13046
Chemicals	7.7	7.2	9.3	331	-3548
Other energy intensive	1.4	2.9	3.0	232	-7726
Rest of Industries	-6.0	-3.8	-1.6	-567	-34691
Energy (incl. Power Generation)	2.2	3.4	4.0	6133	-152913
Services	-9.2	-8.1	-6.1	-163	-2653
Households	-6.8	-7.6	-4.1	-111	-2711
Total	**1.3**	**2.4**	**2.9**	**6387**	**-217287**
EU-USA Scenario	2020	2030	2015-2050	Non abating countries	Abating countries
Industry	4.1	8.1	12.1	900	-7447
Energy Intensive	5.5	7.9	10.3	279	-2713
Metals	-4.0	2.2	5.9	41	-697
Chemicals	23.5	20.5	24.3	126	-521
Other energy intensive	4.0	5.9	7.4	111	-1496
Rest of Industries	3.5	8.2	13.1	621	-4733
Energy (incl. Power Generation)	12.7	28.9	43.2	3881	-8992

Services	-7.5	-7.7	-3.6	-34	-939
Households	0.0	0.7	3.2	53	-1656
Total	**7.2**	**17.1**	**25.2**	**4801**	**-19033**

* Negative values indicate decrease of emissions (no carbon leakage)

** Sectoral carbon leakage rates are based on direct emissions from each sector.

Source: GEM-E3

The calculated leakage rates by industrial sector are within the range reported in the literature; see for example [42], [43] and [44].

As energy intensive industrial production is partly relocated, energy demand tends to increase in the non-abating regions that produce more energy intensive products. As this production is also electricity intensive, emissions from power generation tend to increase in the non-abating regions. In abating regions, using more expensive but less emitting technologies allows for lower carbon emissions in power generation. Thus, emissions of energy sectors in non-abating countries increase while they decrease in abating countries: this leakage observed for sectors is not a leakage through the energy channel (as it is not related to fossil fuel prices) but is a consequence of industrial relocation, thus it is part of the industrial channel.

Industrial leakages by sector are measured as the ratio of the amount of emission increases in the regions not pursuing climate action over the amount of emissions reduced in the regions pursuing climate action. Table 13 shows the industrial leakage rates by sector. The leakage rates shown for industry, services and households correspond to change of emissions in final energy consumption, whereas the rates shown for energy correspond to emissions in primary and secondary (including power generation) energy consumption. The majority of the increased emission amounts in non-abating countries are emitted in power generation implying that the overall leakage rates could be reduced if emission abating measures focusing on power generation could be adopted in non-abating countries.

5.2.5 SENSITIVITY ANALYSIS

For sensitivity analysis purposes two sets of simulations were performed. In the first set alternative tax revenue recycling option are assumed in order to evaluate their impacts on leakage. The second set examines the impact of alternative trade substitution elasticity values on carbon leakage.

5.2.5.1 Tax revenue recycling options

It is reminded that in main simulations state revenues from carbon taxation was recycled as lump-sum transfers to households. The alternative recycling options are defined as follows:

i) Revenues are transferred (as subsidies) to the energy-intensive industries which are more vulnerable in leakage. The subsidy levels are calculated so that production costs of these industries remain similar to reference projection despite rising carbon prices; thus industrial competitiveness is mitigated and leakage should be reduced. The remaining carbon tax revenues are used as lump-sum transfers to households.

ii) Revenues are used to decrease indirect taxation on all products.

Table 14: Impact of alternative carbon tax recycling options on carbon leakage

Carbon leakage rates (cumulatively over 2015-2050)	Carbon revenue recycling options		
	HHs Income	Subsidies to Energy Intensive Industries	Indirect Taxation
EU – Only Scenario	27.7	16.4	27.9
EU – China Scenario	2.9	1.4	2.8

Source: GEM-E3

The results shown in Table 14 confirm that using carbon revenues to subsidize energy intensive industries so as to cancel competitiveness losses significantly decreases carbon leakage. The remaining leakage is due to the changes in global trade structure resulting from the competitiveness losses in non-subsidized industries of abating economies since carbon prices drive higher domestic prices in abating countries despite the subsidies to energy intensive industries. The benefits would be lower if the subsidized energy intensive industries do not pass through the entire subsidies to prices.

The sensitivity analysis also shows that recycling revenues for reducing indirect taxation would not reduce the leakage rates compared to transferring the revenues to households.

5.2.5.2 Trade substitution elasticities

Carbon leakage generated through the industry channel depends on the ease of substitution between domestically produced goods and imported goods; in other words it depends on the extent to which these goods are considered as perfect substitutes. The degree of substitutability between domestically produced goods and imported goods is measured in the GEM-E3 model through the values of the Armington[13] elasticities. High elasticity values indicate that products are relatively homogeneous whereas low elasticity values denote high product differentiation. When industrial products are relatively homogeneous the competitiveness loss incurred by the industries operating in carbon abating regions is expected to be higher than in cases where products are significantly differentiated.

The Armington elasticity values for substitutions between imported and domestically produced goods range between 2 and 4 for all products as used in the basic simulations, except for fossil fuels for which much higher values are assumed (Table 5). For the inner nest of the Armington CES function which splits total imports in imports by country origin, the values of elasticities are higher and range between 4 and 8.

The sensitivity analysis consists in varying the values of the Armington elasticities only for the upper level of the CES nesting, i.e. regarding substitution between domestically produced and imported goods, and in re-estimating the carbon leakage rates by performing the same simulations[14]. Below, two cases are presented corresponding to a halving and a doubling of

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[13] Based on Armington [9] the products are not homogeneous and differentiate at national and international markets, according to production origin.

[14] For each change in the Armington elasticity the model has been recalibrated.

elasticity values relative to the basic model version. The resulting estimations of leakage rates are presented in Table 15.

The sensitivity analysis confirms that the industrial leakage rates depend on the values of the trade substitution elasticities. Higher elasticity values imply higher leakage rates. However, the order of magnitude of leakage rates remains the same, which can be seen that independently of elasticity value cases the leakage rates in the EU-China coalition are much lower than in the EU-Only scenario.

Table 15: Leakage rates under different Armington elasticity values

	Total carbon leakage (2010 – 2050)		
	Halved values	Values as in basic simulation	Doubled values
EU-Only scenario	24.4%	27.7%	34.5%
EU-China scenario	2.6%	2.9%	3.7%

Source: GEM-E3

Additional sensitivity analysis was performed with regard to the Armington elasticities. The elasticities were changed only for specific sectors. We distinguish three groups: i) energy intensive industries, ii) energy sectors and iii) rest of the economy. When elasticity values change (doubled or halved) for one group of industries the elasticities for the other sectors were maintained at their reference values. The results are summarized in Table 16.

Table 16: Leakage rates under differentiated Armington elasticity values by sector

		Total carbon leakage (2010 – 2050)	
		EU-Only scenario	EU-China scenario
Halved values	Energy Intensive industries	27.1%	2.7%
	Energy industries	26.9%	2.8%
	Rest of the economy	25.8%	2.9%
	All industries	24.4%	2.6%
Values as in basic simulation	All industries	27.7%	2.9%
Doubled values	Rest of the economy	31.5%	3.1%
	Energy industries	29.3%	3.1%

	Energy Intensive industries	28.9%	3.3%
	All industries	34.5%	3.7%

Source: GEM-E3

One would expect that changing the elasticities of the sectors that contribute more to the carbon leakage (i.e. energy) would have greater impact. However this is not confirmed by the results and the highest differences in leakage rates are obtained when changing elasticity values for all sectors. The results of the sensitivity analysis also confirm that the dominant factor for determining the order of magnitude of the leakage rate is the composition of the group of abating countries, rather than the intensity of competition in foreign trade.

6 CONCLUSIONS

The GEM-E3 model has been used to quantify the rate of carbon leakage when GHG emission reduction actions are asymmetrically undertaken by countries. The simulations have been performed in a dynamic setting up to 2050 assuming that carbon pricing is the main instrument for reducing carbon emissions. Based on the projections by scenario the leakage rates are calculated which reflect increase of emissions in non-abating countries over emissions decreased in abating countries. The reason of obtaining positive leakage rates is the redistribution of trade of commodities between the countries as a result of changes in the competitiveness of abating countries vis-à-vis the non-abating ones. Leakage that would be due to adjusted international fossil fuel prices is minimal because the scenarios have assumed sufficiently elastic supply of fossil fuels. Therefore the estimated leakage rates mainly reflect leakage through the industrial (or competitiveness) channel.

The size of the economies participating in the emission abating group is important for the leakage rate: an EU-China coalition implies dramatically reduced leakage rates compared to a case where the EU acts alone for emission reduction and even compared to a coalition of the EU with the USA. Although the leaked emission amounts are larger in the EU-China case, their ratio over decreased emissions is very low compared to cases without China's participation, just because the decreased emissions are very high when China participates. Another important factor which explains this result is the effectiveness of the carbon price to reduce emissions which is much higher in countries, such as China, exhibiting high energy and carbon inefficiency compared to OECD countries. Including China, a low cost producer, in the abating coalition also mitigates the adverse effects of weakened competitiveness and thus reduces the leakage rate.

The estimated cumulative leakage rates in the EU alone and in the EU-USA cases are between 25% and 27% which is close to the higher end of the range reported in the literature. It goes down to 2.9% in the EU-China coalition case which is close to the low end of the values in the literature. The carbon leakage computed with the GEM-E3 model lies at the upper bound of similar model results from the EMF29 study [11]. GEM-E3 computes a leakage rate for the EU at 27.7% whereas the mean of EMF29 models is around 20% (but calculated in a limited horizon until 2020).

In absolute terms the increased emissions in non-abating countries are lower than the decreased emissions in abating countries, because of restructuring away from carbon intensive activities induced by the rising carbon prices, despite applying this rise only in abating countries. By decomposing the leakage by sector of activity it is evident that the largest amounts leaked correspond to additional emissions in power generation of the non-abating countries. Measures focusing on reducing emissions in power generation in these countries would greatly help reducing leakages without applying economy wide carbon pricing.

Among the energy intensive sectors, metal production and the chemicals sector are found to present the highest leakage rates. These sectors are characterized by both high energy intensity and high trade exposure. By contrast, the leakage of building materials sectors is much smaller because of lower trade exposure. To this respect, the numerical results are in line with literature on carbon leakage.

The leakage rates are sensitive to the Armington elasticity values which are usually used in computable general equilibrium models. Higher Armington elasticity values imply higher leakage rates. The sensitivity analysis performed using the model has shown that independently of Armington elasticity values the leakage rate is dramatically reduced when China joins the group of abating countries. The order of magnitude of leakage rates by industrial sector seem to be robust independently of Armington elasticity values.

According to model-based sensitivity analysis results, recycling part of carbon revenues to alleviate price effects in energy intensive industries can significantly reduce leakage rates but cannot cancel them out. From a leakage perspective, subsidizing the energy intensive industries is superior to all other schemes of recycling carbon tax revenues.

The model-based simulations presented in this paper have ignored impacts of induced technology change and spillover effects that can effectively reduce carbon leakage rates (as it is shown in study [5] that uses a different version of GEM-E3).

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